ERDC/CRREL TR-15-16

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Review of the Probable Maximum Flood (PMF) Snowmelt Analysis for Success Dam

Steven F. Daly

November 2015

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Final Report

Approved for public release; distribution is unlimited.

Prepared for U.S. Army Corps of Engineers, Sacramento District
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Abstract

This report reviews the initial snowpack distribution assumed to be in place and available for melt in the probable maximum flood (PMF) analysis of Success Dam conducted by the Corps of Engineers. This project reviewed two aspects of the initial snow distribution: the snow-covered area (SCA) distribution and the snow water equivalent (SWE) distribution. We analyzed satellite imagery to determine the daily SCA of the Success Dam watershed from 2000 to 2014. This analysis was based on time-domain filtering of NASA's daily snow product. The SCA of the Success Dam watershed is highly dynamic with large day-to-day variations. The maximum 95th percentile SCA for each elevation band was selected to describe the initial snow cover in place at the start of the PMF analysis. We next reviewed the initial SWE distribution. Above 5000 ft, the initial SWE distribution was greater than the snowmelt that occurred during the PMF and was therefore *heat transfer limited*. In this region the snowmelt runoff during the PMF was insensitive to the amount of SWE. Below 5000 ft, the snowmelt was limited by the initial SWE. Runoff from this region is sensitive to the amount of initial SWE.

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Preface

This study was conducted for the Sacramento District of the Corps of Engineers. The technical monitor was Angela Duren, CENWP-EC-HY.

The work was performed by Dr. Steven Daly (Terrain and Ice Engineering Group, Stephen Newman, Chief), U.S. Army Engineer Research and Development Center (ERDC), Cold Regions Research and Engineering Laboratory (CRREL). At the time of publication, Timothy Pangburn was the Director of the Remote Sensing/GIS Center of Expertise. The Deputy Director of ERDC-CRREL was Dr. Lance Hansen, and the Director was Dr. Robert Davis.

At CRREL, Timothy Baldwin performed the geographic information system (GIS) analysis, Blaine Morriss completed the time-domain filtering (TDF) analysis of the MOD10A1 snow products, and Callan George made the additional calculations.

COL Bryan S. Green was the Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

Acronyms and Abbreviations

CRREL	U.S. Army Cold Regions Research Engineering Laboratory
ERDC	Engineer Research and Development Center
fSCA	Fractional Snow-Covered Area
GIS	Geographic Information System
NDSI	Normalized Difference Snow Index
NASA	National Aeronautics and Space Administration
OEM	Old Enterprise Mill
PMF	Probable Maximum Flood
QKA	Quaking Aspen Station (Snow Course)
QUA	Quaking Aspen Station (Automated Gage)
SCA	Snow-Covered Area
SWE	Snow–Water Equivalent
TDF	Time-Domain Filtering
USACE	U.S. Army Corps of Engineers

Unit Conversion Factors

Multiply	By	To Obtain
acres	4,046.873	square meters
acre-feet	1,233.5	cubic meters
cubic feet	0.02831685	cubic meters
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
inches	0.0254	meters
miles (U.S. statute)	1,609.347	meters
square miles	2.589998 E+06	square meters

Executive Summary

This report reviews the initial snowpack distribution assumed to be in place and available for melt in the probable maximum flood (PMF) analysis of Success Dam conducted by the U.S. Army Corps of Engineers (USACE 2013). We conducted our review because of the significant impact of snowmelt on the PMF results and the scarcity of data available to describe the snowpack conditions. We reviewed two aspects of the initial snow distribution: the snow-covered area (SCA) distribution and the snow–water equivalent (SWE) distribution over the Success Dam watershed.

The Corps PMF snowmelt analysis (USACE 2013) divided the watershed into ten 1000 ft elevation bands. The PMF assumed that an initial SWE depth was in place in each elevation band and was available to melt (USACE 2013). The initial SWE ranged from a maximum of 54.4 in. at 8000–9000 ft to a minimum of 4 in. at 3000–4000 ft. The Corps PMF snowmelt analysis assumed that no snow was in place below 3000 ft. Each elevation band was implicitly assumed to be 100% snow covered. The initial distribution of the snowpack resulted in 232.7 square miles (59.7%) of the watershed covered with snow and a total SWE volume of 267×10^3 acre-ft.

For our review, we at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) analyzed satellite imagery to determine the daily SCA of the Success Dam watershed from 2000 to 2014. This analysis was based on time-domain filtering (TDF) of NASA's (National Aeronautics and Space Administration) daily MOD10A1 snow product. TDF results in virtually cloud-free daily snow maps displaying the fractional SCA (fSCA) of pixels not obscured by clouds. The pixel size is roughly 500 × 500 m, and the Success Dam watershed is covered by 4710 pixels. We estimated the fSCA of each pixel for each day for 2000–2014.

The CRREL SCA analysis found that the SCA of the Success Dam watershed is highly dynamic with large day-to-day variations. This study considered various options for selecting the appropriate SCA to use in determining the initial snow distribution. We calculated the SCA statistics for each day of the winter season and selected the maximum 95th percentile SCA for each elevation band to describe the initial snow cover in place at the

start of the analysis as being sufficiently conservative without being extreme. The total watershed SCA that resulted from selecting the maximum 95th percentile SCA for each elevation band was 101.6 square miles (26.03% of the watershed). This is greater than the total watershed SCA observed on 99.5% of the days with SCA greater than zero. The SWE volume that resulted from combining the SWE depth for each elevation band used in the PMF study with the 95th percentile SCA for each elevation band was 178×10^3 acre-ft.

We next reviewed the initial SWE distribution used in the Corps PMF study (USACE 2013). Above 5000 ft, the initial SWE distribution was greater than the snowmelt that occurred during the PMF. The snowmelt in this region was therefore *heat transfer limited*. In this region, the snowmelt runoff during the PMF was insensitive to the amount of SWE given that the SWE was greater than the snowmelt amount. Below 5000 ft, the snowmelt was limited by the initial SWE. Runoff from this region was sensitive to the amount of initial SWE. Unfortunately there is no information on the actual SWE in this region of the Success Dam watershed. Based on the work of others and the SCA analysis described in this report, the distribution selected in this region seems appropriate.

The 100% snow cover area used in the PMF study is also a requirement of the HEC-HMS elevation-band snow model (USACE 2010a). HEC-HMS is not currently capable of including the impact of SCA in the elevation-band snow-model option that was used for the PMF runoff calculations. An alternative is to use the gridded snow-model option instead.

1 Introduction

Success Dam, a U.S. Army Corps of Engineers (USACE) flood control project, is located in southern California on the Tule River. This report reviews the initial snowpack distribution assumed to be in place and available for melt in the probable maximum flood (PMF) analysis of Success Dam conducted by the Corps of Engineers (USACE 2013).

A significant amount of the PMF runoff from the watershed upstream of Success Dam is from snowmelt (USACE 2013). Therefore, we conducted our review because of the significant impact of snowmelt on the PMF results and the scarcity of data available to describe the snowpack conditions. The Corps PMF snowmelt analysis divided the watershed into ten 1000 ft elevation bands, assigning an initial snow–water equivalent (SWE) depth to each band. The initial SWE ranged from a maximum 54.4 in. at 8000–9000 feet to a minimum of 4 in. at 3000–4000 ft. The Corps PMF snowmelt analysis assumed that no snow was in place below 3000 ft. Each elevation band was implicitly assumed to be 100% snow covered. The initial distribution of the snowpack resulted in 232.7 square miles (59.7%) of the watershed covered with snow and a total SWE volume of 267×10^3 acre-ft.

The initial snowpack distribution resulted from the combination of SWE and snow-cover area (SCA) assigned to each elevation band. The SWE assigned to each elevation band in the PMF analysis of Success Dam does not seem unreasonable. However, the implicit assumption of 100% SCA in each elevation band is likely to be unduly conservative. The impact of SCA on snowmelt calculations has long been recognized (see, for example, Anderson 1973). However, it has not been practical to quantitatively observe the SCA of a moderate-to-large-size watershed at a resolution and frequency that is useful. As a result, the snowmelt component of the HEC-HMS elevation-band snow model assumes that each subbasin or elevation band has 100% SCA at all times (USACE 2010a).

A new satellite imagery analysis tool developed at the U.S. Army Cold regions Research and Engineering Laboratory (CRREL) for application in remote austere watersheds now allows the SCA to be automatically mapped using NASA’s (National Aeronautics and Space Administration) daily

MOD10A1 snow product. This process, referred to as Time-Domain Filtering (TDF), results in virtually cloud-free daily snow maps. The daily snow maps display the fractional SCA (fSCA) at a pixel resolution of 500 × 500 m, and the Success Dam watershed is covered by 4710 pixels. We used TDF to determine the fSCA of each pixel for each day for 2000–2014.

The CRREL SCA analysis found that the SCA of the Success Dam watershed is highly dynamic and varies significantly from day to day but that the SCA analysis was consistent with the topography of the watershed and the estimated air temperature range. We considered various options for selecting the appropriate SCA to use in determining the initial snowpack distribution. The SCA selected is conservative but not extreme, and it significantly modifies the snowpack distribution compared to the initial snowpack distribution assumed to be in place at the start of the PMF analysis of Success Dam (USACE 2013).

We next reviewed the initial SWE distribution used in the Corps PMF study (USACE 2013). Above 5000 ft, the initial SWE distribution was greater than the snowmelt that occurred during the PMF. The snowmelt in this region was therefore *heat transfer limited*. In this region, the snowmelt runoff during the PMF was insensitive to the amount of SWE given that the SWE was greater than the snowmelt amount. Below 5000 ft, the snowmelt was limited by the initial SWE. Runoff from this region was sensitive to the amount of initial SWE. Unfortunately there is no information on the actual SWE in this region of the Success Dam watershed. Based on the work of others and the SCA analysis described in this report, the distribution selected in this region seems appropriate.

2 Success Dam Watershed

The Success Dam watershed is located on the western slope of the southern Sierra Nevada Mountains in California (USACE 2013). The 390-square-mile drainage area above the dam is largely steep mountainous terrain. Watershed elevations range from about 10,000 ft in the mountains to 550 ft at the dam. Figure 1 shows the layout of the watershed; and the USACE reports (1998, 2013) further describe the watershed characteristics, vegetation, climate, precipitation, and flooding. The locations of data collection stations in the watershed are shown in Figure 1 and are described in Table 1.

Figure 1. The Lake Success watershed.

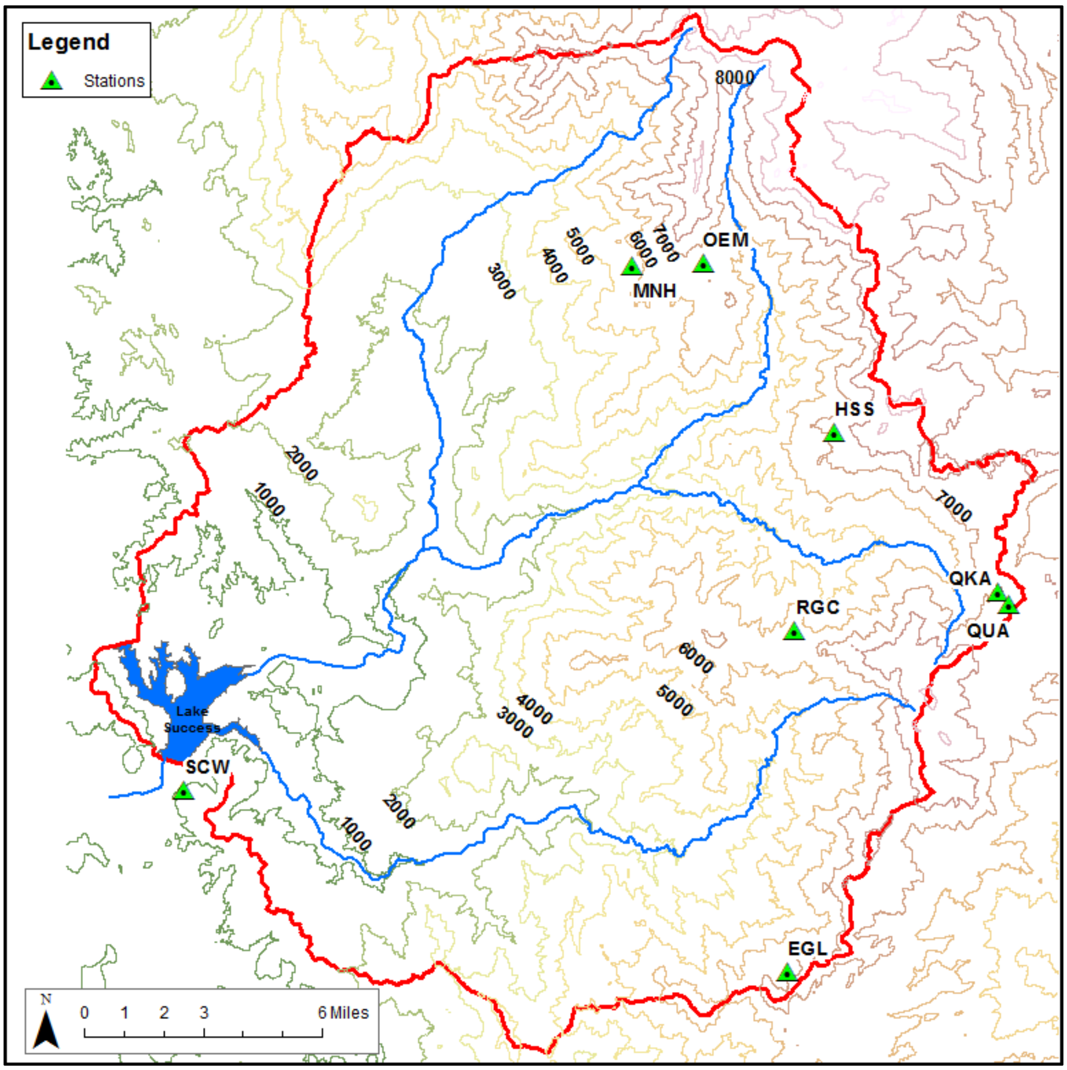


Table 1. SWE and Air Temperature stations located in Success Dam watershed.

ID	Station	Parameter	Rate	Longitude	Latitude	Elevation (ft)	Period of Record	Operator
OEM	Old Enterprise Mill	SWE	Yearly/ Monthly	−118.678	36.243	6600	1937–2014	CA Dept. of Forestry and Fire Protection
QKA	Quaking Aspen	SWE	Yearly/ Monthly	−118.545	36.122	7000	1937–2014	Tule River Ranger District
QUA	Quaking Aspen	SWE	Daily	−118.53994	36.11754	7200	1981–2014	CA Dept. of Water Resources
EGL	Eagle Creek	Air Temp.	Hourly	−118.641	35.983	6700	1995–2009	USACE
HSS	Hossack	Air Temp.	Hourly	−118.619	36.181	7100	1995–2009	USACE
MNH	Mountain Home	Air Temp.	Hourly	−118.71	36.242	5400	1995–2009	USACE
RGC	Rogers Camp	Air Temp.	Hourly	−118.637	36.108	6200	1995–2009	USACE
SCW	Success	Air Temp.	Hourly	−118.9139	36.05	590	1995–2009	USACE

2.1 Topography

We analyzed the topography of the Success Dam watershed on a pixel-by-pixel basis using pixels defined in the MOD10A1 snow product imagery. MOD10A1 snow product imagery is in the form of “tiles” with each tile approximately 1200 × 1200 km in area and containing approximately 2400 × 2400 pixels. Each pixel is roughly 500 × 500 m in size. The Sacramento District provided a shapefile of the Success Dam watershed boundary. Combining the watershed shapefile and the MOD10A1 tile produced a shapefile that contained 4710 polygons that described each MODIS pixel within the watershed. Only the MODIS pixels whose center point fell within the watershed were included in the analysis. We used ArcMap 10.1 SP1 to determine the elevation, slope, and aspect of each MODIS pixel by using a DEM called "mos_prj_ft" that the Sacramento District provided (A. Duren, personal communication). The cell size of this DEM was a little over 30 ft. We determined the elevation, slope, and aspect of each pixel using ArcGIS (ESRI 2011). Specifically, we calculated the elevation and slope by using the “Zonal Statistics as Table” tool; and we calculated the mean aspect by using a custom script tool (Beyerhelm 2013).

Figure 2 shows the distribution of the pixel aspects. The watershed faces largely to the southwest. We also followed the example of the PMF study (USACE 2013) and divided the watershed into 1000 ft elevation bands. Figure 3 and Table 2 show the area of each elevation band.

Figure 2. The aspect distribution of Success Dam watershed pixels.

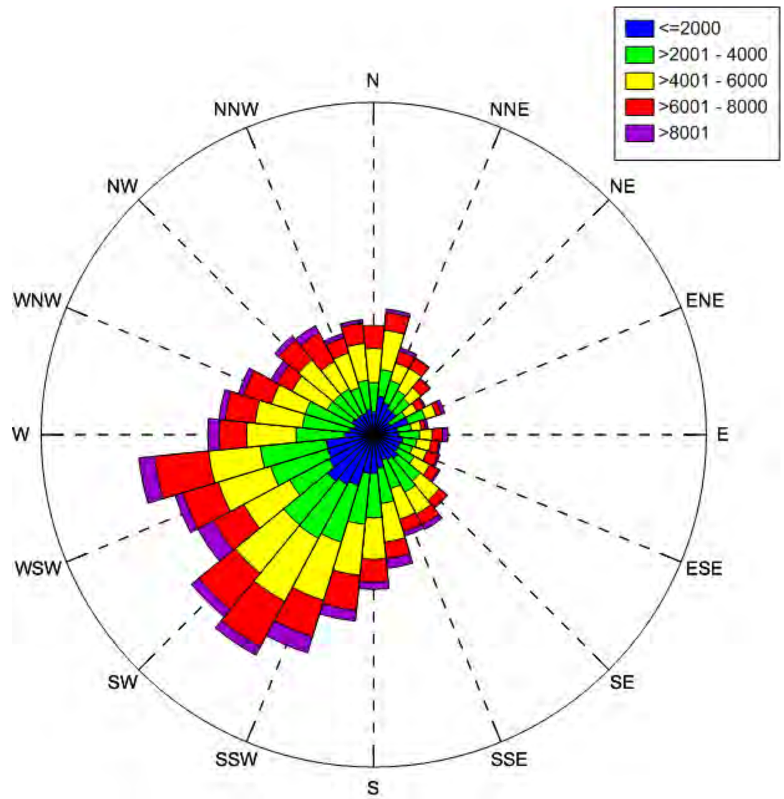


Figure 3. The area of each elevation band.

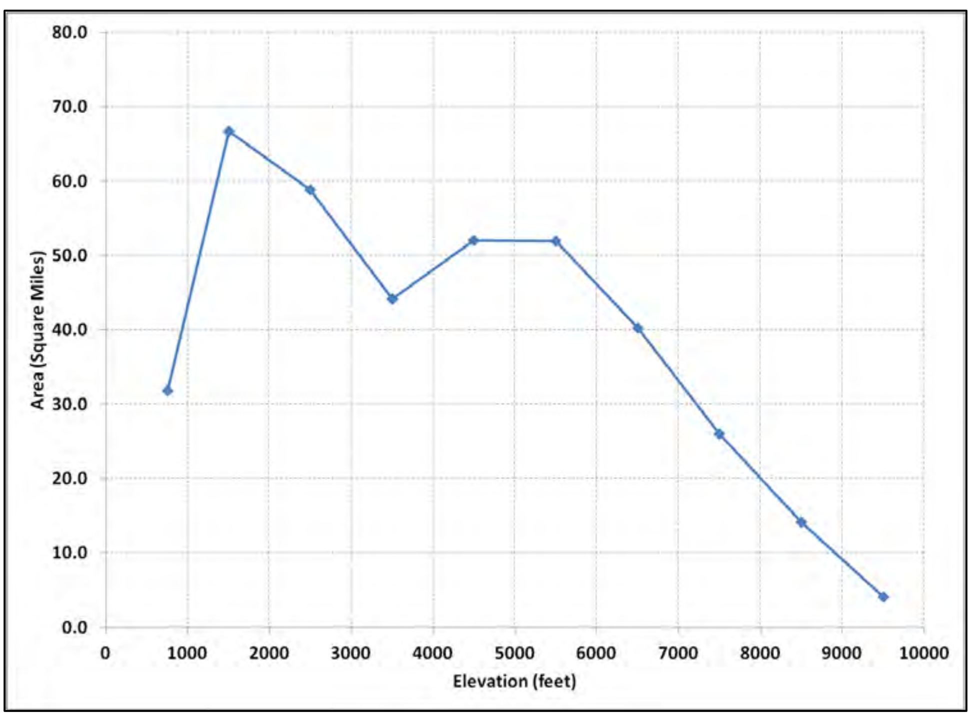


Table 2. The area of each elevation band and the total area.

Elevation Band	Area (Square Miles)	Cumulative Area From the Peak (Square Miles)
515–1000	31.9	390.1
1000–2000	66.7	358.2
2000–3000	58.8	291.5
3000–4000	44.2	232.7
4000–5000	52.0	188.5
5000–6000	51.9	136.5
6000–7000	40.3	84.6
7000–8000	26.0	44.3
8000–9000	14.2	18.2
9000–10,000	4.1	4.1

2.2 Air temperature

We calculated the statistics of the daily average air temperature for each day of the winter season to provide an overview of the wintertime conditions by using the "Cyclic Analysis Statistics Math Tool" of HEC-DSSVue (USACE 2009). Hourly air temperature records are available at five stations in the Success Dam watershed (Table 1). The statistics were calculated based on the entire period of record for each station listed in Table 1. The daily average air temperature was rarely lower than 32°F (indicated in Figure 4) at any of the stations throughout the winter. It is interesting to note the relatively rapid rise of the temperature at the Success Dam compared to the other stations starting in mid-winter and continuing through early summer. Figure 5 shows the daily average minimum temperature observed at each station for each day of the winter season. The daily average minimum air temperatures were below 32°F for all the stations except Success Dam for December through April. These higher temperatures at Success Dam attest to the relatively warm conditions at the downstream and lowest end of the watershed.

The hourly elevation of the 32°F isotherm of the watershed was estimated through linear interpolation of the hourly air temperatures recorded at the five stations. The elevation of the stations ranged from 590 to 7200 ft (although the highest four stations are all located above 5400 ft). We found that elevations above the 32°F isotherm were always colder than elevations below and that temperature inversions were all short lived; none lasted longer than a day. The 32°F isotherm provides information on the

conditions that control heat transfer between the snowpack and the atmosphere and the snowpack persistence as snow is more likely to melt when exposed to air temperatures above 32°F. Figure 6 shows the minimum, maximum, and average elevations of the daily 32°F isotherm throughout the winter. The average 32°F isotherm rarely falls below 6000 ft, while the minimum has reached as low as 2000 ft in isolated cases.

Figure 4. Daily average air temperatures for each day of the winter.

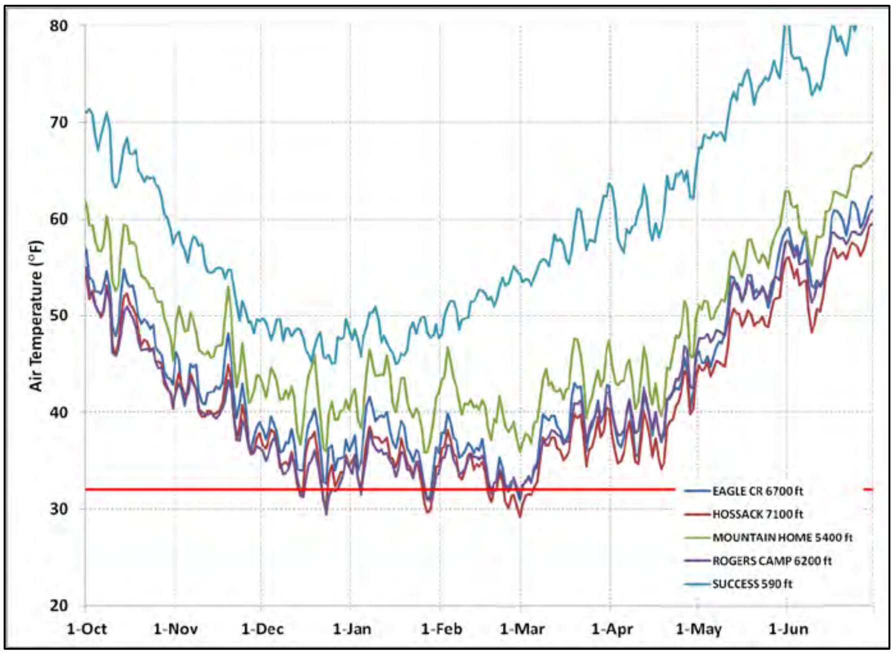


Figure 5. Minimum daily average air temperatures for each day of the winter.

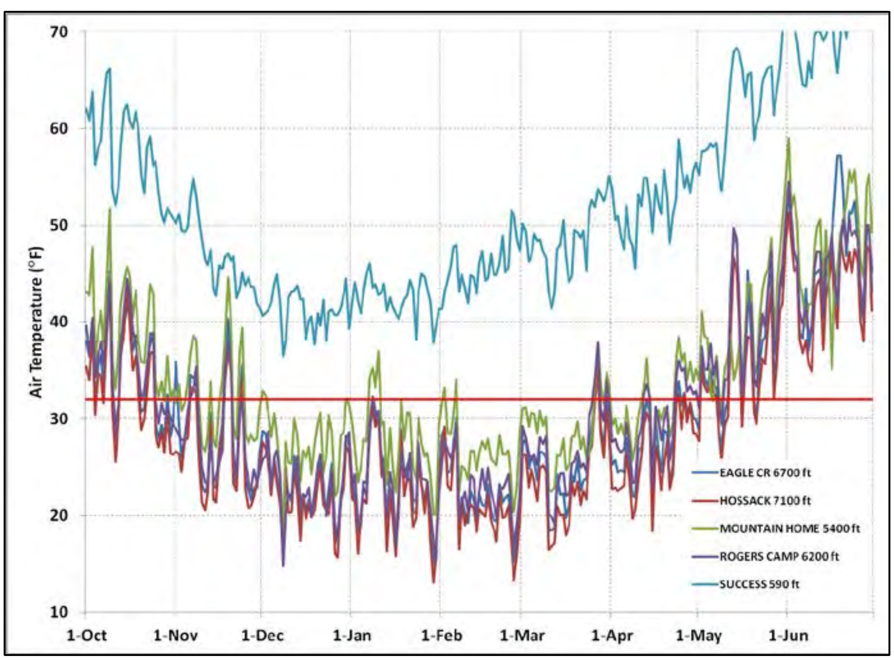
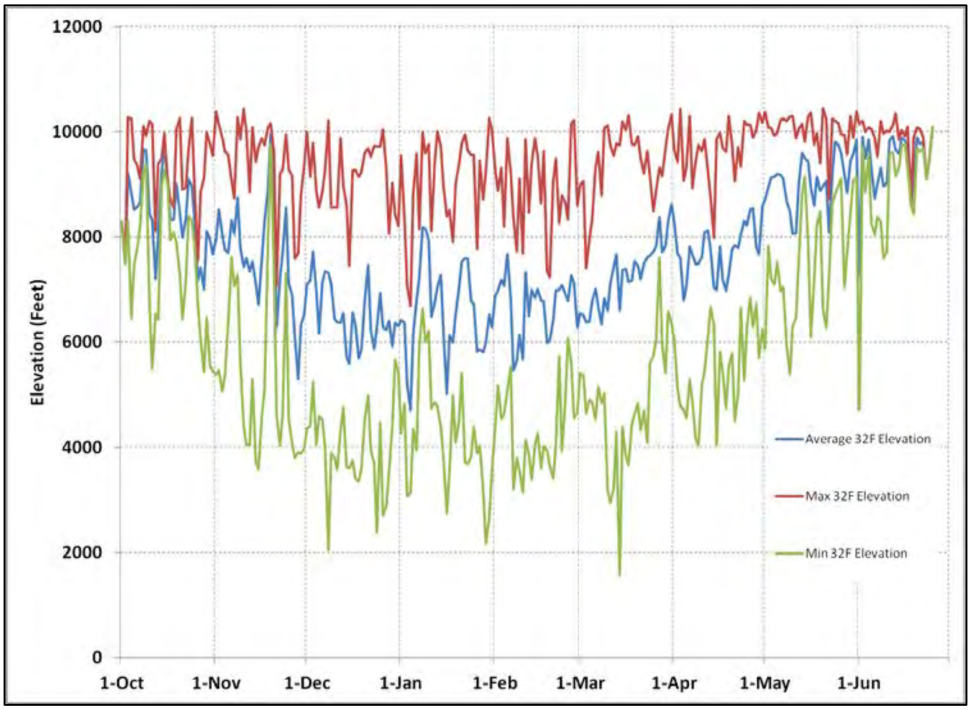


Figure 6. The elevation of the 32°F isotherm.



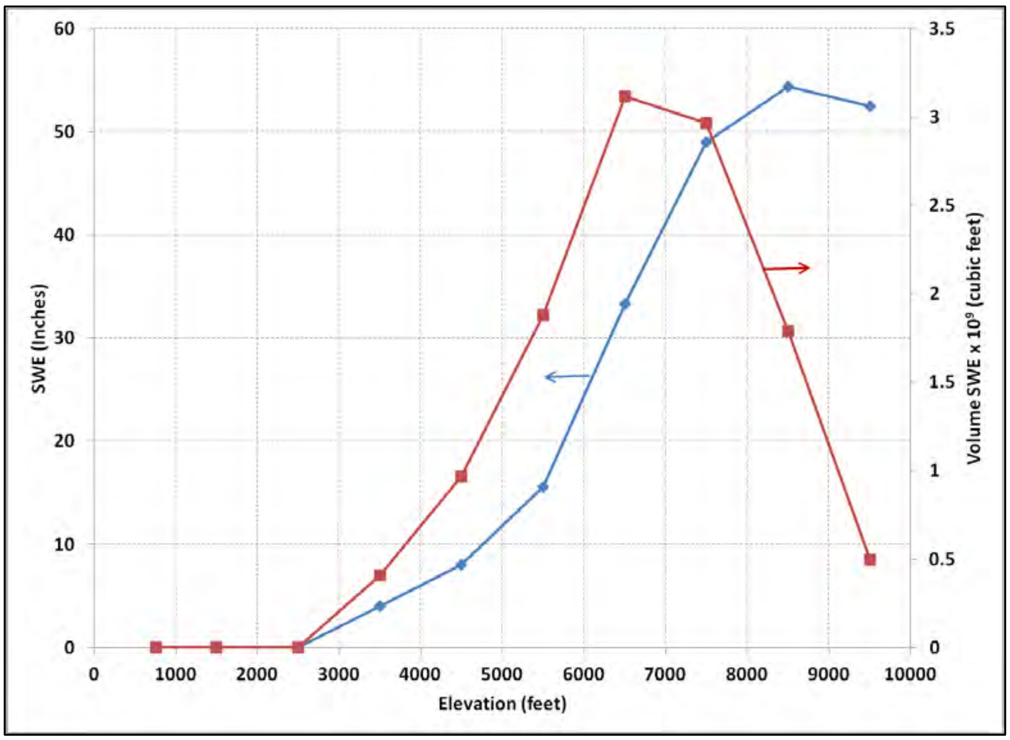
3 PMF Initial Snow Conditions

The initial snowpack distribution assumed to be in place at the start of the PMF analysis of Success Dam (USACE 2013) are shown in Table 3 and displayed in Figure 7. In that initial analysis, the volume of SWE for each elevation band was found by multiplying the SWE assigned to each band (Table 3) by the area of the elevation band (Table 2).

Table 3. PMF Starting Conditions (USACE 2013).

Project Datum (ft)	Snow Density (ft)	Snow Depth (in.)	Snow–Water Equivalent (in.)
515–1000	No Snow on the Ground		0
1000–2000	No Snow on the Ground		0
2000–3000	No Snow on the Ground		0
3000–4000	0.40	10	4.0
4000–5000	0.40	20	8.0
5000–6000	0.39	40	15.6
6000–7000	0.37	90	33.3
7000–8000	0.35	140	49.0
8000–9000	0.32	170	54.4
9000–10,000	0.30	175	52.5

Figure 7. The PMF SWE distribution by elevation.



4 Snow-Covered-Area Analysis

4.1 Background

Our analysis of SCA is based on the NASA-developed SCA product, MOD10A1, the MODIS/Terra Snow Cover Daily L3 Global 500 m Grid (Hall et al. 2006), which provides a daily estimate of the fSCA of the globe at a 500 m pixel resolution. The SCA is estimated using the normalized difference snow index (NDSI), which leverages the contrasting reflectance of snow in the visible and shortwave-infrared regions of the spectrum (Hall et al. 2006). The fSCA is estimated using an empirical relationship between fSCA and NDSI. This process may have difficulties in heavily forested areas (Salomonson and Appel 2004). Areas obscured by clouds are masked out of the MOD10A1 product based on the MODIS cloud mask (MOD35). The MODIS cloud mask (MOD35) uses a host of algorithms and 19 of MODIS's 36 bands to determine if clouds are contained in the MODIS image (Ackerman et al. 2010).

The large and changeable areas obscured by clouds in each daily SCA product represent a significant impediment to the use of the MOD10A1 SCA product in water resources investigations. CRREL has developed a new technique, referred to as Time Domain Filtering (TDF), to address this issue of cloud obscuration (Morriss et al., forthcoming). In general, we find mean cloud persistence, or the average time between cloud-free scenes, to be less than a day at Terra MODIS's temporal scale (approximately 1 day). This cloud-cover transience gives us the opportunity to fill in gaps in the current day's imagery with recent data. Because we use multiple days' imagery as inputs, we choose to limit our outputs to SCA that is persistent on a multi-day scale. Each output pixel's value is based on up to 16 daily images though only the two most recent cloud-free images influence the value of the outputs. This approach limits errors of commission in snow cover that arise from cloud and cloud shadow misclassification in the MOD10A1 detection algorithms. If SCA is present in both of the two most recent cloud-free images, the output pixel's value is set to the fSCA value of the most recent image. If either pixel's value in the cloud-free pair is snow free, the output pixel is assumed to be snow free. This requirement sometimes filters transient SCA from the output product in addition to spurious SCA but creates a conservative and robust delineation of SCA extent. In the rare occurrence that a pixel does not have any cloud-free readings in the 16 input scenes, the output is cloud.

4.2 Overview

Our study analyzed SCA within the Success Dam watershed by determining the fSCA for each pixel for each day by using the TDF analysis of the MOD10A snow product. We determined the fSCA for each of the 4710 MODIS pixels in the watershed for each of the 5405 days in the period of record, which spanned from 4 March 2000 through 20 December 2014. There were 45 days of fSCA data missing due to gaps in the MOD10A data. There were 2715 days with SCA of which 2133 days (78.6%) had unique data; 582 days with SCA (21.4%) were duplicates caused by the presence of clouds.

We determined the total area covered by SCA for each day of the period of record by summing the fSCA of all the pixels in the watershed and multiplying the result by the area of a MODIS pixel. Figure 8 shows the time series of total watershed SCA. It is interesting to note the "spikiness" of the total SCA. The area of the watershed that is continuously snow covered each winter is relatively small, generally less than 20 square miles. Periods when much larger areas are snow covered last only a few days.

Figure 8. The total watershed SCA.

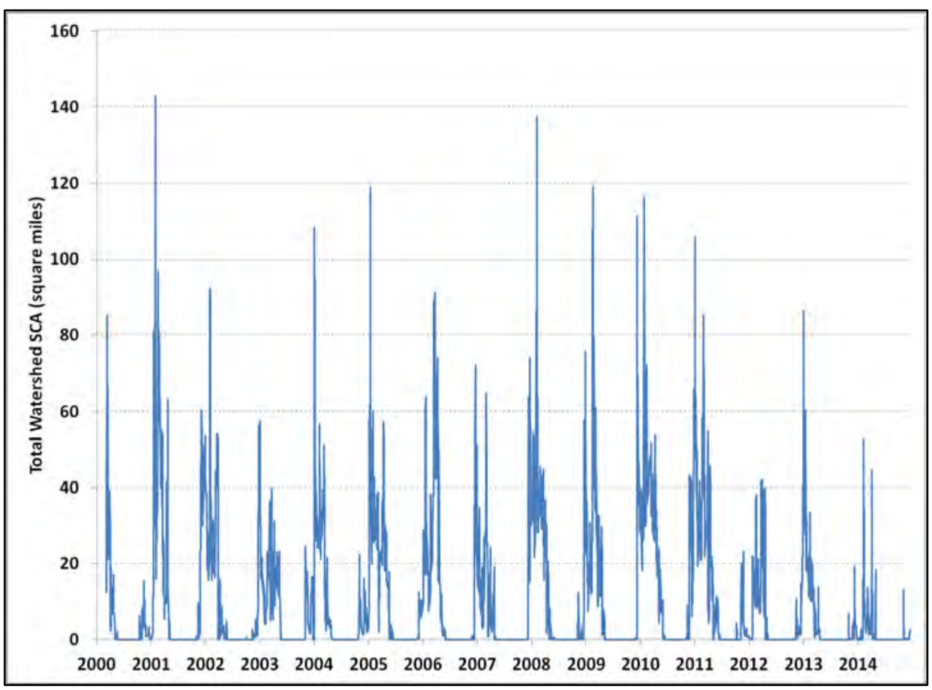


Figure 9 shows the time series of total watershed SCA as a percentage of the total Success Dam watershed. This demonstrates that the SCA generally ranges between 5% and 10% of the watershed area. Figure 10 displays

the statistics of SCA for each day in the winter and includes the daily average SCA and the maximum and minimum recorded SCA.

Figure 9. The total watershed SCA as a percentage of the watershed area.

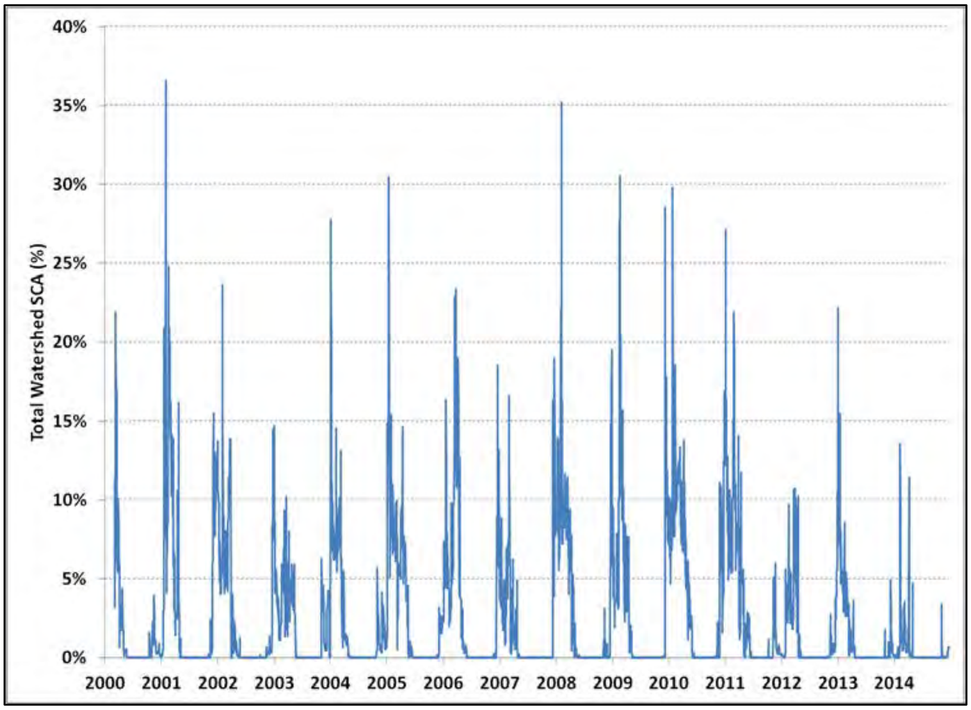
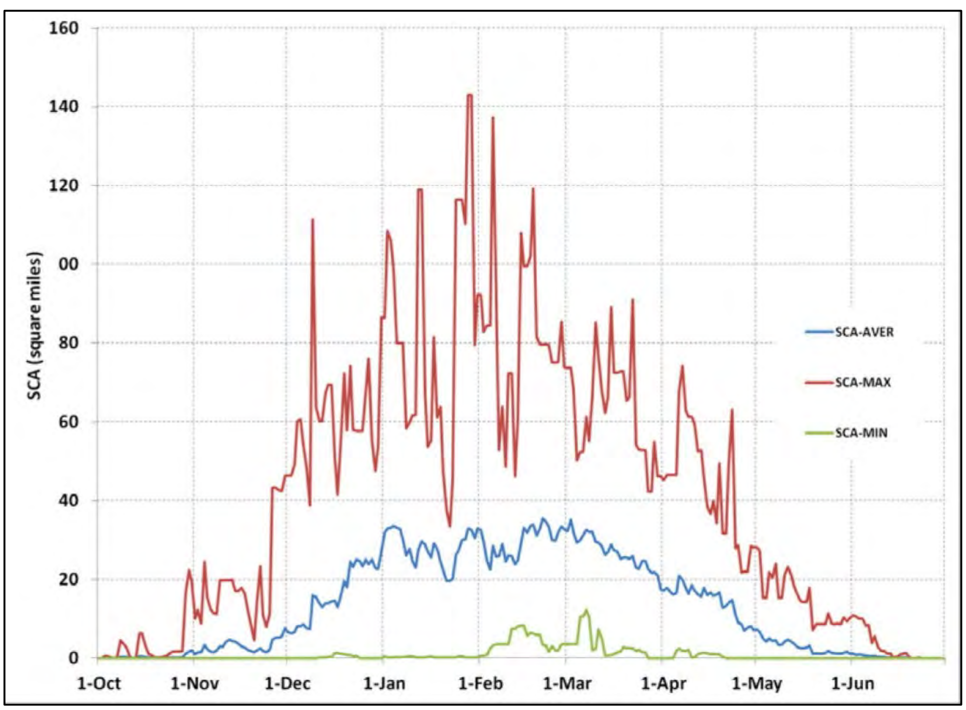


Figure 10. Average, maximum, and minimum total watershed SCA for each day of the winter.



4.3 Daily SCA results

For demonstrational purposes, we selected several days in the period of record to view in detail. On 29 January 2001, the largest total watershed SCA over the period of record occurred (Figure 11). A second image displays the SCA map seven days later on 5 February 2001 (Figure 11). The dynamic nature of the SCA can be seen in the dramatic reduction in SCA over these seven days.

Figure 11. The SCA on 29 January 2001 and seven days later on 5 February 2001.

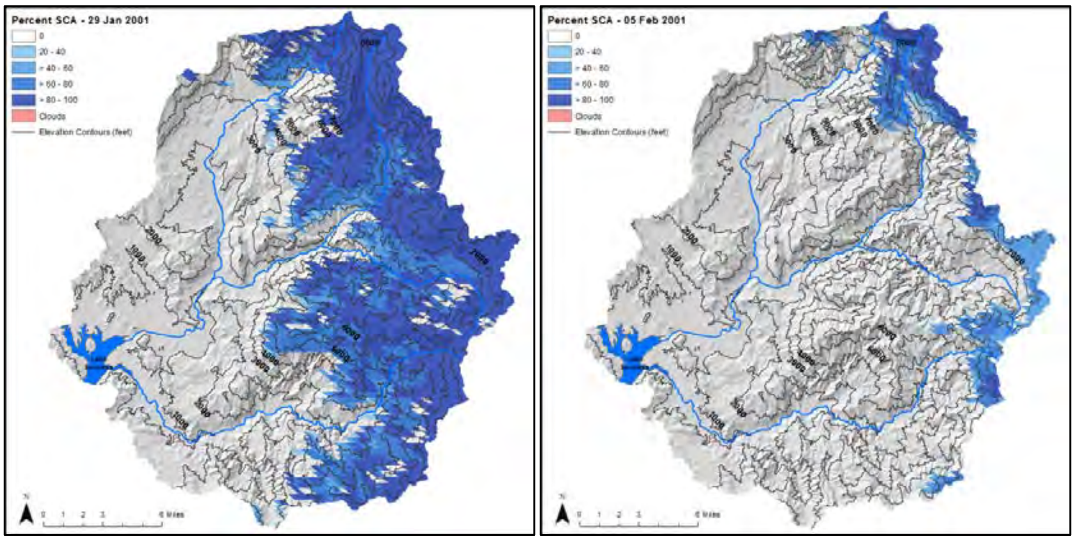


Figure 12 shows the estimated SCA for 12 January 2005. This is also a date when one of the largest watershed SCA was recorded. The pixels marked as cloud covered mean that the MODIS cloud mask interpreted the conditions over these pixels as cloud covered for 16 consecutive days or more on 12 February 2005. Note that some areas at higher elevations are snow free and that these areas match snow free areas recorded on 29 January 2001 (Figure 11).

Figure 13 shows the estimated SCA for 18 February. This date also had one of the largest watershed SCA recorded. In large part, the SCA follows the elevation contours, but not exclusively so. There are several instances where the SCA extends downhill in isolated salients, essentially cutting across the elevation contours. These downhill SCA projections may result from spatial variations in the distribution of snowfall that are not entirely coincidental with the contour locations.

Figure 12. The SCA on 12 January 2005.

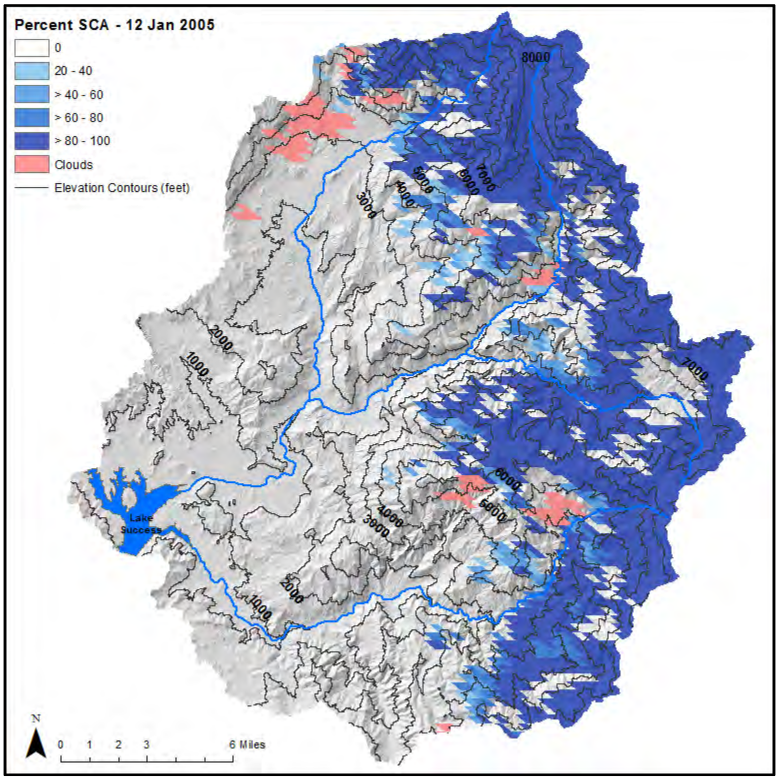
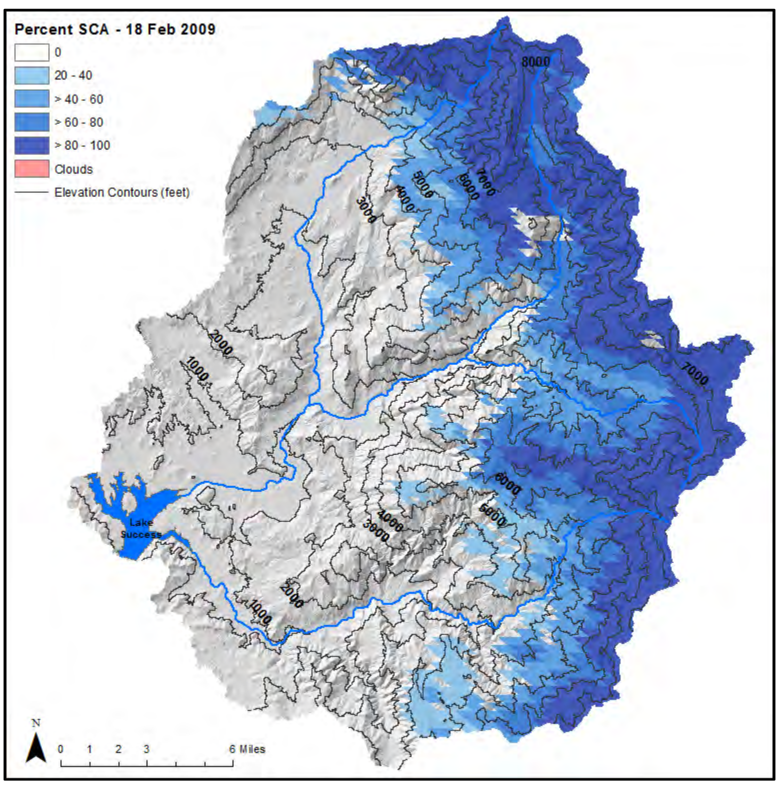


Figure 13. The SCA on 18 February 2009.



4.4 General SCA distribution

We first analyzed the general distribution of SCA throughout the watershed by calculating the longest duration each winter that each pixel was continuously covered by snow (fSCA > 20%). We then averaged these durations over the period of record and mapped them (Figure 14). This map also includes the elevation contours, showing that the distribution of SCA very closely follows these contours. This close agreement of the SCA duration and the contours is taken as a partial confirmation of the TDF process.

We used the total watershed average daily SCA shown in Figure 10 to estimate the elevation of the average effective daily snow line. Here, the effective snow line is defined by the elevation above which the area equals the total watershed SCA. We used the information in column 3 of Table 2 to interpolate the elevation that corresponded to the area of the total watershed SCA of each day. This is a rough measure of the snow line, but the close relation of the snow line and the 32°F isotherm can be seen in Figure 15. These close results also suggest that the TDF process provided reasonable and accurate results.

Figure 14. The average continuous SCA duration each winter by pixel.

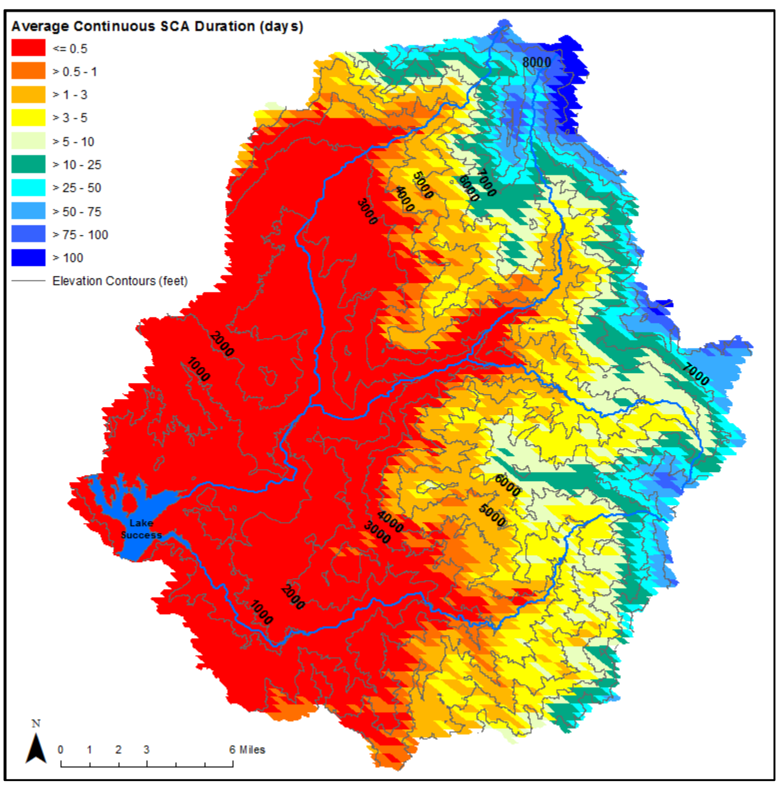
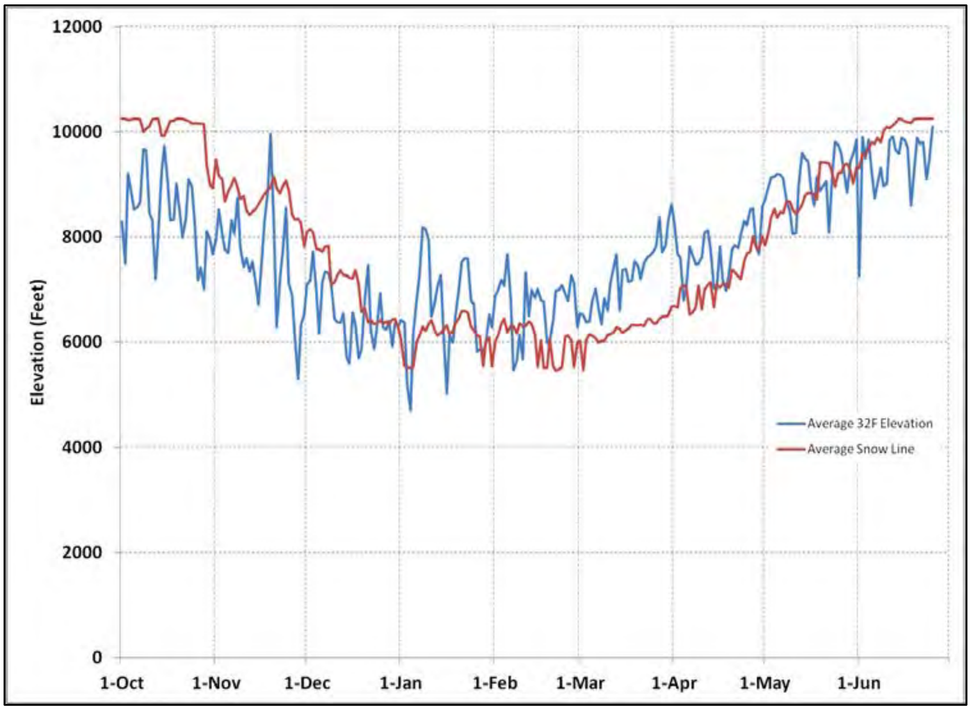


Figure 15. The average elevation of the 32°F isotherm and the snow line.



We also calculated the SCA for each elevation band for each day over the period of record, having determined the elevation for each pixel as described earlier. The SCA for an elevation band on day i, SCA^i_{eb}, was

$$SCA^i_{eb} = \frac{1}{n}\sum_{j=1}^{n} fSCA^i_j \quad (1)$$

where

n = the number of pixels in the elevation band and
$fSCA_j$ = the fSCA of the jth pixel.

We then determined the SCA statistics for each day of the year by using the "Cyclic Analysis Statistics Math Tool" of HEC-DSSVue (USACE 2009). Figure 16 shows the daily average SCA for each elevation band. In this figure, the daily average SCA for each elevation band drops rapidly as the elevation band elevation decreases, in agreement with Figure 14. Figure 17 shows the daily 95th percentile SCA for each elevation band. The 95th percentile SCA is greater than 95% of the SCA recorded on that day of the year. The 95th percentile SCA, while greater in value than the average, also drops rapidly as the band elevation decreases, especially below 7000 ft.

Figure 16. The average SCA on each day of winter for each elevation band.

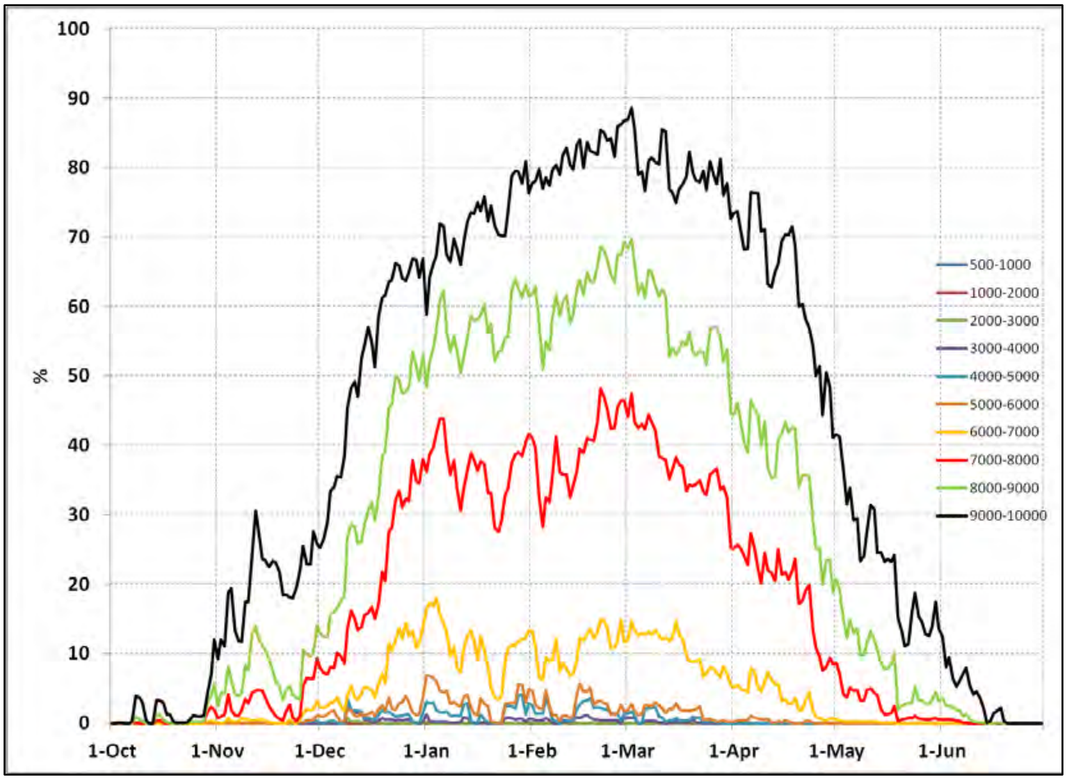
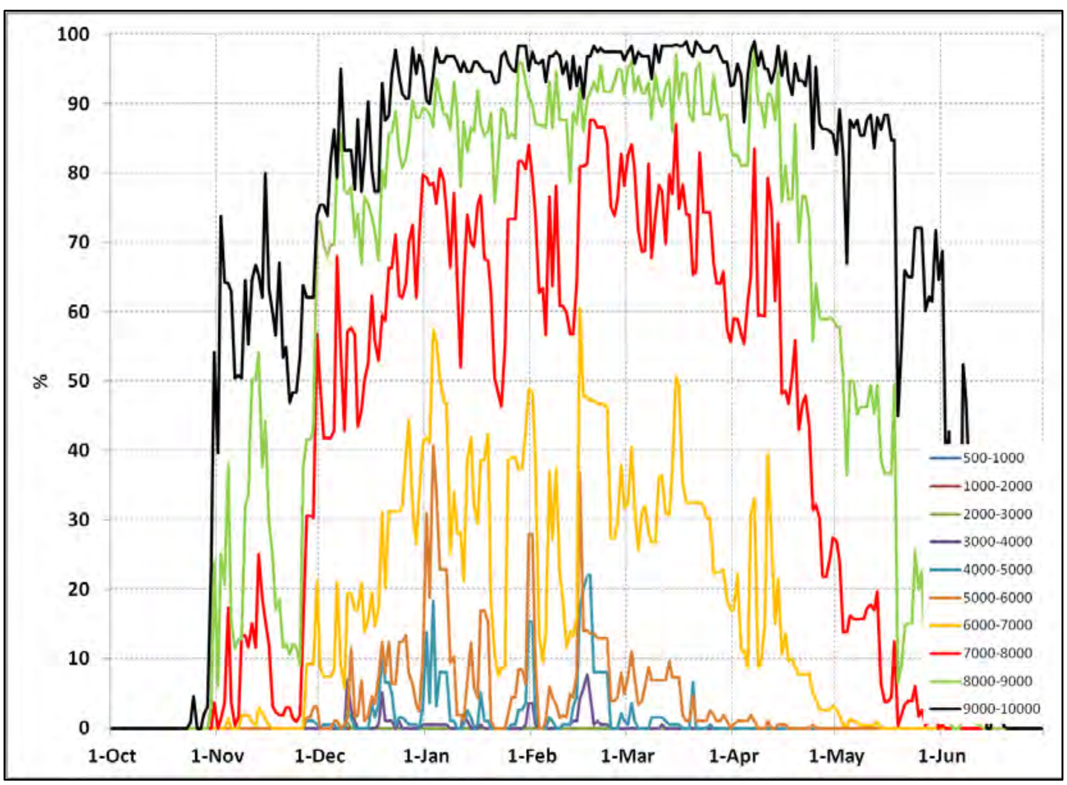


Figure 17. The 95th percentile SCA on each day of the winter for each elevation band.



5 Application of SCA to the PMF Determination

The starting conditions of the PMF study of the Success Dam (USACE 2013) had snow extending from the highest elevations down to 3000 ft as shown in Table 3. There was no accounting for the likely snow covered area in each band. The SCA for each band was implicitly assumed to be 100%. As can be seen in the previous section, the likelihood of SCA decreases rapidly as the elevation decreases.

There is no discussion regarding the inclusion of SCA in a PMF study in any of the relevant guidance documents of the USACE. Therefore, we decided to review four possible options for selecting the SCA for the elevation bands. The results are shown in Table 4 and are displayed in Figure 18 and Figure 19.

5.1 SCENARIO A

We based this scenario on the average SCA in each band that was observed on the day of the maximum SWE observed at the Quaking Aspen station (QUA) over the period from 2000 to 2014. As it is likely that extreme events will happen at or around the time of maximum SWE, we selected the SCA corresponding to the date of the maximum SWE for each elevation band for each year from 2000 through 2014. We averaged the annual SCAs to arrive at a final value for each elevation band. These results were not particularly conservative as the total watershed SCA of this scenario is only greater than the total watershed SCA observed on 82% of the days with a total SCA greater than zero.

5.2 SCENARIO B

We based this scenario on the maximum SCA in each band that was observed on the day of the maximum SWE observed at the Quaking Aspen station (QUA) for the years 2000 through 2014. This is similar to SCENARIO A except that we selected the maximum SCA observed on the date of the maximum SWE. The results are shown in Table 4 and are displayed in Figure 18. These results are more conservative than SCENARIO A. The total watershed SCA of this scenario is greater than the total watershed SCA observed on 96.3% of the days with a total SCA greater than zero.

5.3 SCENARIO C

This scenario used the average maximum 30-day SCA. The daily SCA for each elevation band was converted to a time step of 30 days with the value of each 30-day variable set equal to the average of the 30 days that it spanned. Then the maximum 30-day value was selected for each winter. The average over all winters was then calculated to arrive at the average maximum 30-day SCA. These results are more conservative than SCENARIO A but slightly less than SCENARIO B. The total watershed SCA of this scenario is greater than the total watershed SCA observed on 94.1% of the days with a total SCA greater than zero.

5.4 SCENARIO D

This scenario used the maximum 95th percentile SCA. We selected the maximum 95th percentile SCA, displayed in Figure 17, from each elevation band. These results are more conservative than the other scenarios. The total watershed SCA of this scenario is greater than the total watershed SCA observed on 99.5% of the days with a total SCA greater than zero.

5.5 Selection of the SCA Scenario

The selection of the SCA scenario to use is complicated because of the highly dynamic nature of SCA in the Success Dam watershed as shown in Figure 8 and Figure 9. The accumulation of SWE requires time for successive snowfall events to accumulate. Highly ephemeral SCA responds to each snowfall event but quickly ablates before significant SWE can accumulate. The SCA scenario selected has to strike a balance between being sufficiently conservative in representing the largest area of the watershed that could be covered with snow when the PMF occurred and having sufficient time in place for the SWE to accumulate. We selected the maximum 95th percentile SCA (SCENARIO D) for each elevation band as being sufficiently conservative without representing transient events where some of the SCA had little SWE. The total watershed SCA that results from selecting the maximum 95th percentile SCA for each elevation band is 101.6 square miles (26.03% of the watershed). This is greater than the total watershed SCA observed on 99.5% of the days with SCA greater than zero. The SWE volume that results from combining the SWE depth used in the PMF study with the 95th percentile SCA for each elevation band is 178×10^3 acre-ft.

Table 4. The SCA by elevation and results for each scenario.

Elevation Band	PMF (%)	A (%)	B (%)	C (%)	D (%)
515–1000	-	0.0	0	0.0	0.0
1000–2000	-	0.0	0	0.0	0.0
2000–3000	-	0.0	0	0.0	0.8
3000–4000	100	0.0	0.5	2.9	7.7
4000–5000	100	0.1	0.5	6.8	22.0
5000–6000	100	1.6	9.7	11.2	40.7
6000–7000	100	18.0	45.4	27.4	60.6
7000–8000	100	54.0	83.0	64.9	87.6
8000–9000	100	74.8	97.4	84.8	97.7
9000–10,000	100	87.7	99.3	93.3	99.0
	PMF	A	B	C	D
Total SCA (square miles)	232.7	36.4	63.3	54.4	101.6
Total SCA (%)	59.7	9.3	16.2	13.9	26.0
% Days Less Than or Equal to Total SCA	100	82.0	96.3	94.1	99.5
Total SWE (acre-ft × 10^3)	266.94	91.09	144.69	115.87	177.63

Figure 18. The SCA by elevation band for each scenario.

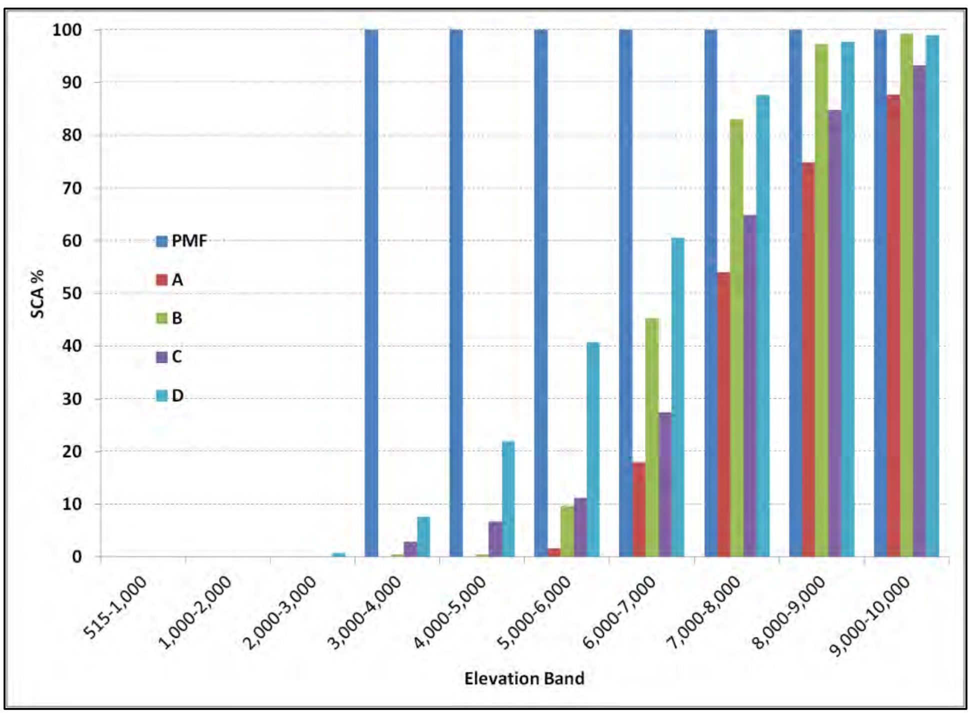
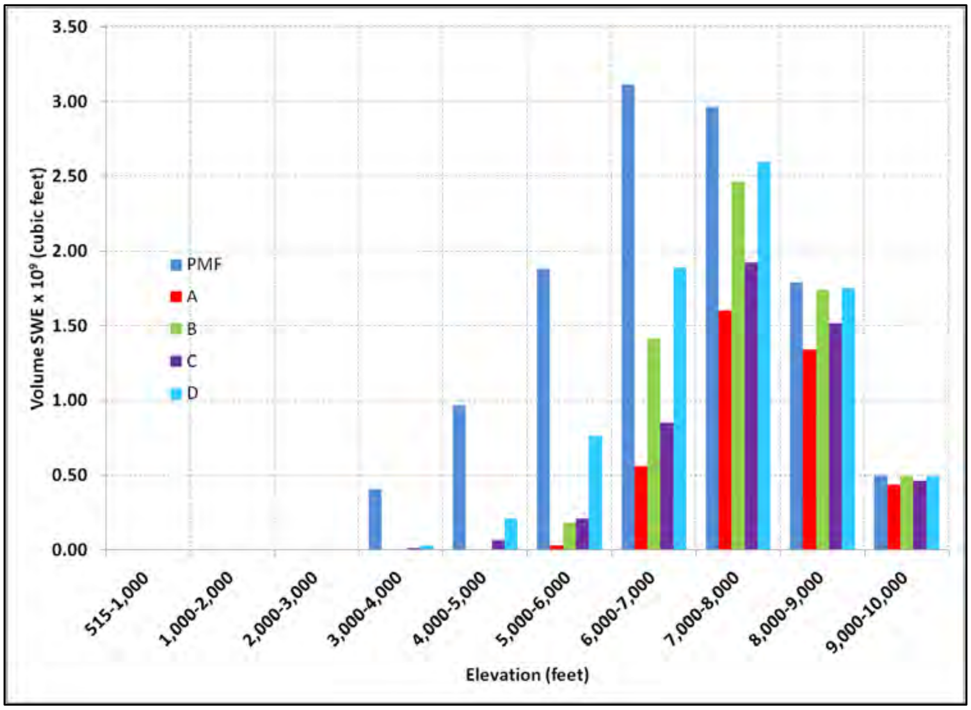


Figure 19. The volume of SWE by elevation band for each scenario.



6 SWE Analysis

This section reviews the initial SWE distribution used in the PMF analysis. First, we compare the initial SWE to the SWE measured in the Success Dam watershed at the stations listed in Table 1. We then determine the impact of the initial SWE distribution on the snowmelt calculated during the PMF.

There are three locations where SWE is observed in the Success Dam watershed (Table 1): an automated SWE gage providing daily observations (Quaking Aspen [QUA]) that has been in operation since 1981 and two snow courses (Quaking Aspen [QKA] and Old Enterprise Mill [OEM]) where data have been collected since 1937. The snow course data were collected only a few times over the course of each winter, generally around the first of the month.

The annual maximum SWE measured at the SWE gage (QUA) and the two snow courses (QKA and OEM) was compiled over the period of record for each source. Observations at the snow courses were not as frequent as at the snow gage. As a result, the snow courses did not capture the annual peak as faithfully as the snow gage. The average annual maximum at QKA is about 93% of the average annual maximum recorded at QUA, and the average annual maximum at OEM is about 83% of the average maximum recorded at QUA. We should note that the all-time maximum SWE recorded by any of the three sites was 62.5 in., recorded at QKA on 1 February 1998.

The statistics of the annual maximum SWE were calculated using a log-normal distribution using HEC-SSP (USACE 2010b). The statistics are listed in Table 5 and shown in Figures 20–22. Figure 23 shows a comparison of the SWE statistics and the initial distribution of SWE used in the PMF. The comparison is valid only for the elevation bands in which the SWE sites are located. It can be seen that the initial SWE falls between about a 10% and 5% annual probability (10-year to 20-year annual return period). This comparison in and of itself does not say much about the appropriateness of the initial SWE distribution.

Table 5. Statistics of annual maximum SWE for sites in the Success Dam watershed.

Annual Probability (%)	Return Period (years)	QKA (in.)	OEM (in.)	QUA (in.)
0.2	500	83.1	105.3	109.3
0.5	200	68.9	85.9	91.0
1	100	59.0	72.6	78.3
2	50	49.8	60.4	66.4
5	20	38.6	45.8	51.8
10	10	30.8	35.8	41.6
20	5	23.5	26.6	31.8
50	2	13.9	15.1	19.1
80	1.25	8.2	8.5	11.5
90	1.11	6.3	6.4	8.8
95	1.05	5.0	5.0	7.1
99	1.01	3.3	3.1	4.7

Figure 20. A frequency plot for Quaking Aspen (QUA).

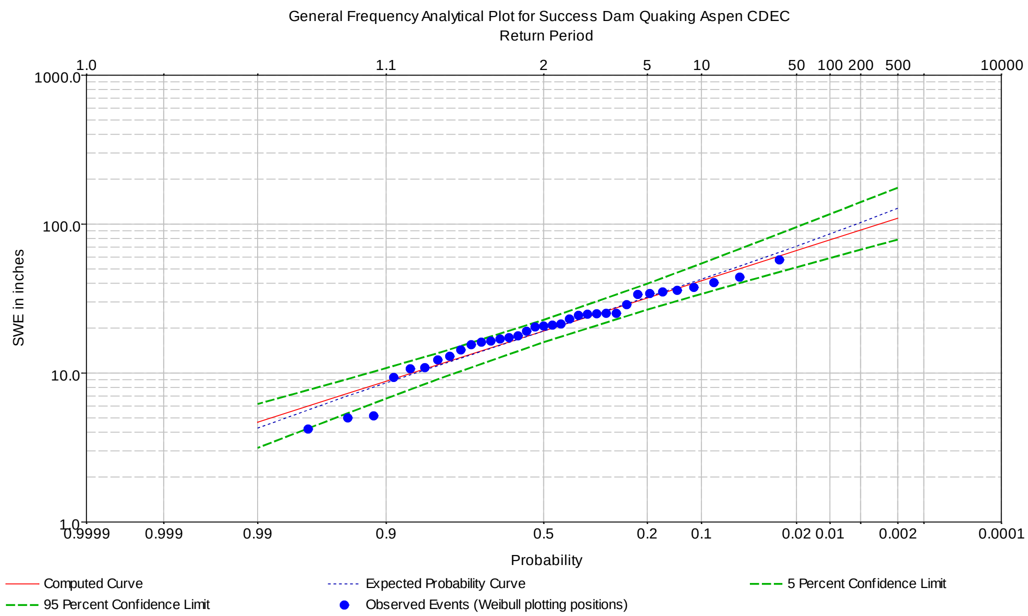


Figure 21. A frequency plot for the Old Enterprise Mill snow course (OEM).

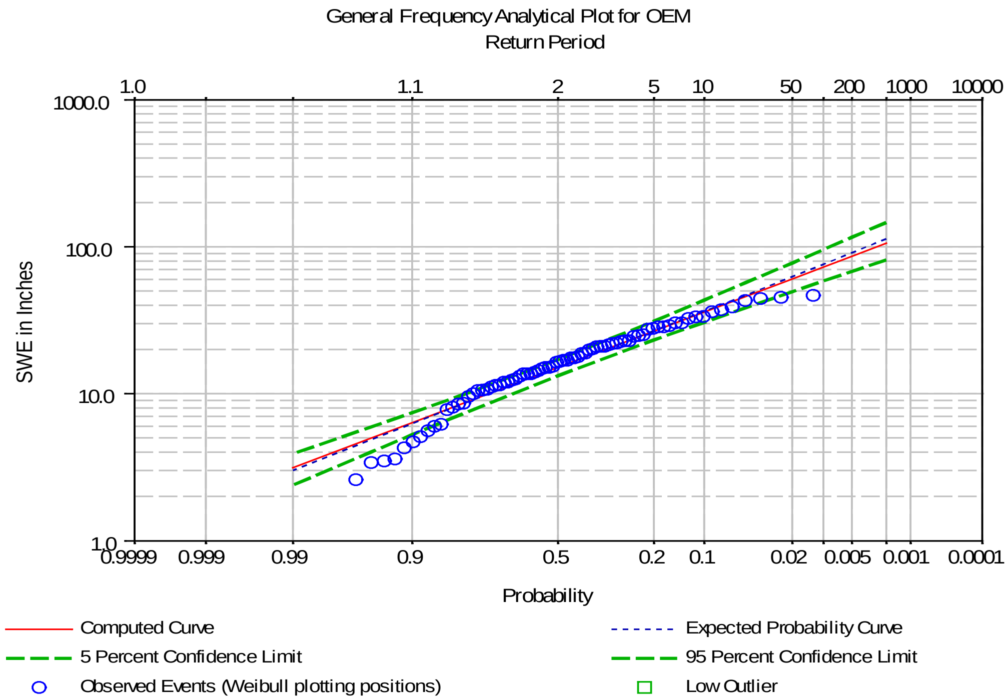


Figure 22. A frequency plot for the Quaking Aspen snow course (QKA).

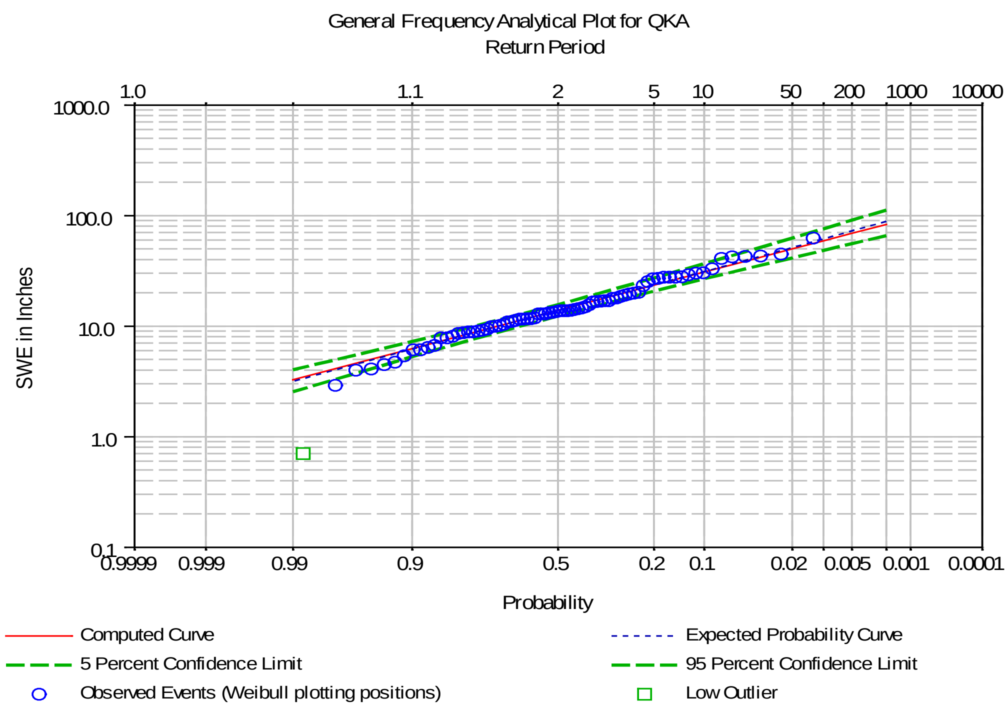
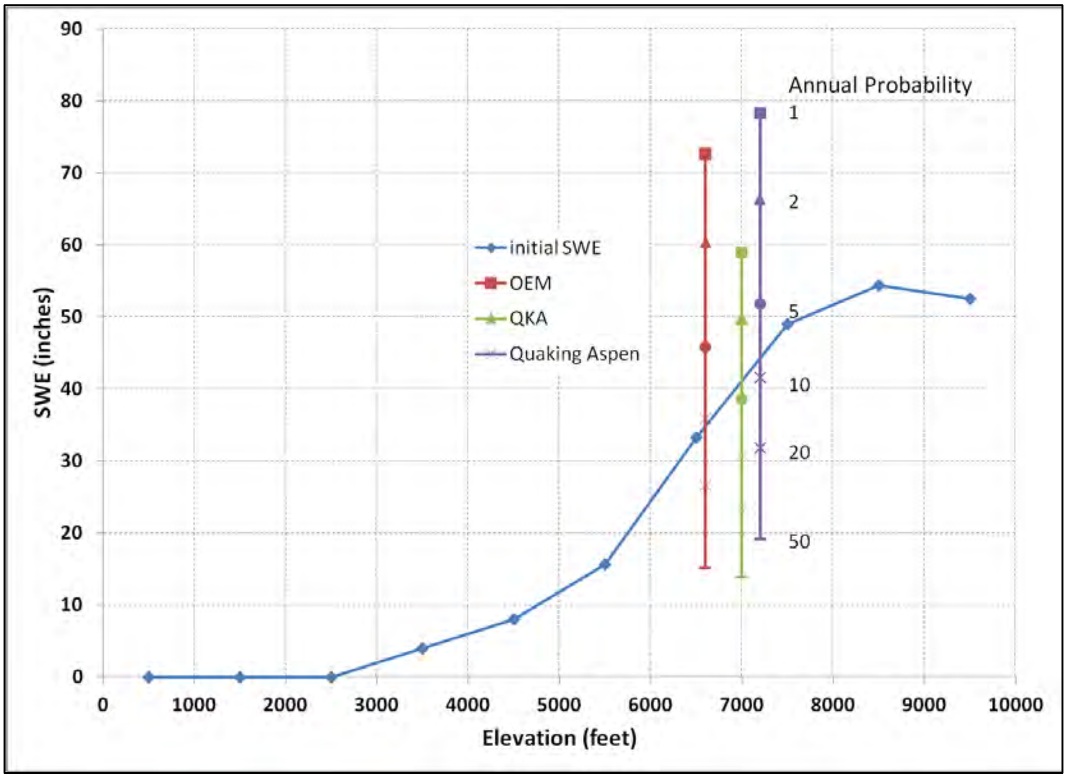


Figure 23. A comparison of the annual probability estimated at each of the SWE sites and the initial SWE distribution of the PMF.



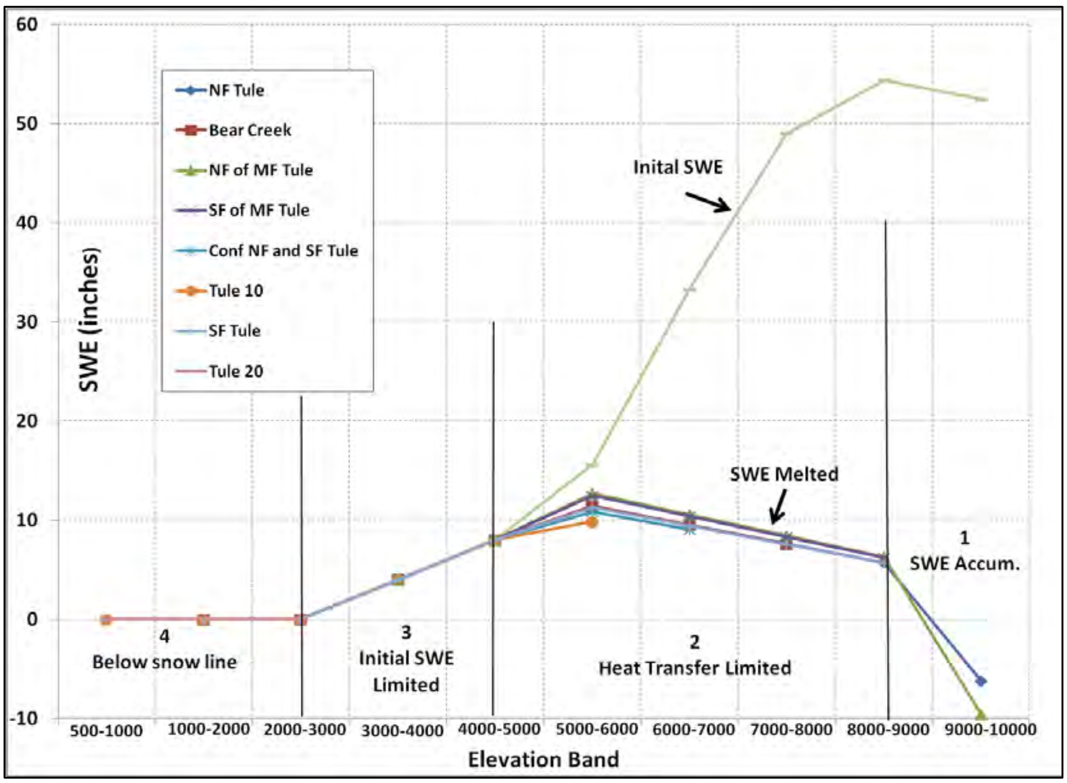
Next, we determined the impact of the initial SWE distribution on the snowmelt calculated during the PMF analysis. Figure 24 shows the SWE that was melted for each elevation band. One can see that the SWE distribution can be divided into four regions, starting at the highest elevations.

1. In the highest elevation, the snow did not melt but actually increased during the PMF analysis. This reflects the subfreezing temperatures that existed at this high elevation during the event.
2. In the next region, the SWE was greater than the snowmelt that occurred during the PMF. The snowmelt in this region was *heat transfer limited*. The snowmelt runoff during the PMF was insensitive to the amount of SWE given that the SWE was greater than the snowmelt amount. This region covered the 5000–6000, 6000–7000, 7000–8000, and 8000–9000 ft elevation bands.
3. In the third region, the snowmelt was limited by the initial SWE amount. Runoff from this region was sensitive to the amount of initial SWE. This region covered the 3000–4000 ft band (4 in. of initial SWE) and the 4000–5000 ft band (8 in. of initial SWE)

4. The fourth region is below the snow line and contributed no snowmelt during the PMF. This region covered the 550–1000, 1000–2000, and 2000–3000 ft bands.

Above 5000 ft, the initial SWE distribution was greater than the snowmelt that occurred during the PMF. Therefore, in this region, the PMF results were insensitive to the actual amount of SWE and the initial SWE distribution appropriate. Below 5000 ft, the snowmelt equaled the initial SWE distribution, indicating that the snowmelt was limited by the initial SWE. Unfortunately there is no information on the actual SWE in this region of the Success Dam watershed. Based on the work of others (Rice et al. 2011) and the SCA analysis above, the distribution selected in this region seems appropriate.

Figure 24. The calculated SWE melted during the PMF analysis and the initial SWE for each elevation band. (Note that SWE melted is shown as positive; SWE increases during the PMF analysis are shown as negative.)



7 Snow Melt Modeling

The inclusion of SCA in the snowmelt modeling will have two major impacts. The first is that the rate of snowmelt reaching the soil surface of each elevation band will be reduced by the SCA fraction. This is apparent when we describe the rate of snowmelt generated, R, as

$$R = m_f A\left(T_a - T_m\right) \tag{2}$$

where

m_f = the melt factor,
A = the area measure of the elevation band,
T_a = the air temperature, and
T_m = the melt temperature (generally set as 32°F).

When SCA is included, R becomes

$$R = C_{SCA} m_f A\left(T_a - T_m\right) \tag{3}$$

where C_{SCA} = SCA of the elevation band.

The second impact is that the total volume of runoff from an elevation band will be reduced by the SCA fraction. The impacts on the total volume can be significant as described in the previous section. Snow models that rely on calibration for estimating melt factors may need to recalibrate when SCA is included.

8 Summary

This report reviewed the initial snowpack distribution assumed to be in place at the start of the PMF analysis of Success Dam (USACE 2013). The PMF snowmelt analysis divided the watershed into elevation bands covering 1000 ft in elevation and assigned a snow–water equivalent (SWE) depth to each band. The initial SWE ranged from a maximum 54.4 in. at 8000–9000 ft to a minimum of 4 in. at 3000–4000 ft. No snow was assumed below 3000 ft. Each elevation band was implicitly assumed to be 100% snow covered. The initial distribution of the snowpack resulted in 232.7 square miles (59.7%) of the watershed covered with snow and a total SWE volume of 267×10^3 acre-ft.

CRREL analyzed satellite imagery to determine the SCA of the Success Dam watershed from 2000 to 2014. This analysis was based on TDF of NASA's daily MOD10A1 snow product. TDF results in virtually cloud-free daily snow maps displaying the fSCA of pixels not obscured by clouds. The pixel size is roughly 500 × 500 m. The Success Dam watershed is covered by 4710 pixels. The fSCA was estimated for each pixel for each day for 2000–2014.

The CRREL SCA analysis found that the SCA of the Success Dam watershed is highly dynamic with large day-to-day variations. We considered various options for selecting the appropriate SCA to use in determining the initial SWE distribution and calculated the SCA statistics for each day of the winter season. We selected the maximum 95th percentile SCA for each elevation band was selected as being sufficiently conservative without being extreme. The total watershed SCA that results from selecting the maximum 95th percentile SCA for each elevation band is 101.6 square miles (26.03% of the watershed). This is greater than the total watershed SCA observed on 99.5% of the days with SCA greater than zero. The SWE volume that results from combining the SWE depth for each elevation band used in the PMF study with the 95th percentile SCA for each elevation band is 178×10^3 acre-ft.

We reviewed the initial SWE distribution used in the PMF study. Above 5000 ft, the initial SWE distribution was greater than the snowmelt that occurred during the PMF. The snowmelt in this region was therefore *heat transfer limited*. In this region, the snowmelt runoff during the PMF was insensitive to the amount of SWE given that the SWE was greater than the

snowmelt amount. Below 5000 ft, the snowmelt was limited by the initial SWE. Runoff from this region was sensitive to the amount of initial SWE. Unfortunately there is no information on the actual SWE in this region of the Success Dam watershed. Based on the work of others and the SCA analysis described in this report, the distribution selected in this region seems appropriate.

The 100% snow cover area used in the PMF study is also a requirement of the HEC-HMS elevation band snow model. HEC-HMS is not currently capable of including the impact of SCA in the elevation-band snow-model option that was used for the PMF runoff calculations. An alternative is to use the gridded snow model option instead. Additionally, other approaches could be used that could conserve the volume of runoff.

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REPORT DOCUMENTATION PAGE

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OMB No. 0704-0188

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1. REPORT DATE *(DD-MM-YYYY)*
November 2015

2. REPORT TYPE
Technical Report/Final

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Review of the Probable Maximum Flood (PMF) Snowmelt Analysis for Success Dam

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Steven F. Daly

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Engineer Research and Development Center (ERDC)
Cold Regions Research and Engineering Laboratory (CRREL)
72 Lyme Road
Hanover, NH 03755-1290

8. PERFORMING ORGANIZATION REPORT NUMBER

ERDC/CRREL TR-15-16

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Corps of Engineers, Sacramento District
1325 J Street, Room 1513
Sacramento, CA 95814

10. SPONSOR/MONITOR'S ACRONYM(S)
USACE

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This report reviews the initial snowpack distribution assumed to be in place and available for melt in the probable maximum flood (PMF) analysis of Success Dam conducted by the Corps of Engineers. This project reviewed two aspects of the initial snow distribution: the snow-covered area (SCA) distribution and the snow water equivalent (SWE) distribution. We analyzed satellite imagery to determine the daily SCA of the Success Dam watershed from 2000 to 2014. This analysis was based on time-domain filtering of NASA's daily snow product. The SCA of the Success Dam watershed is highly dynamic with large day-to-day variations. The maximum 95th percentile SCA for each elevation band was selected to describe the initial snow cover in place at the start of the PMF analysis. We next reviewed the initial SWE distribution. Above 5000 ft, the initial SWE distribution was greater than the snowmelt that occurred during the PMF and was therefore *heat transfer limited*. In this region the snowmelt runoff during the PMF was insensitive to the amount of SWE. Below 5000 ft, the snowmelt was limited by the initial SWE. Runoff from this region is sensitive to the amount of initial SWE.

15. SUBJECT TERMS

Hydrology	Probable maximum flood	Snowmelt
MODIS	Remote sensing	Snow modeling
	Snow-covered area	Snow–water equivalent

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER *(include area code)*
Unclassified	Unclassified	Unclassified	SAR	43	